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E. S. Buice, H. Yang, S. T. Smith, R. J. Hocken, D. L. Trumper, D. Otten, R. M. Seugling

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Controller strategy for a 6 DOF piezoelectric translation stage

Eric S. Buice[1,*], Hua Yang[1], Stuart T. Smith[1], Robert J. Hocken[1], David L. Trumper[2], David Otten[2], and Richard M. Seugling[3]
[1] *Center for Precision Metrology, UNC Charlotte, NC 28223, USA.*
[2] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA.*
[3]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
**Corresponding author:* esbuice@uncc.edu *(E.S. Buice)*

Abstract

A controller for the third generation, 6 degree-of-freedom (DOF) piezoelectric translation stage shown in Figure 1 is presented. This was tested by monitoring all six coordinate motions using an orthogonal array of six, high-resolution capacitance gages. The full 6 DOF matrix transformations and controller block diagrams for this system have been measured and the system operated under closed loop control. Results of early experiments to determine the 21 open loop response functions as well as preliminary results showing the closed loop response for the 3 linear translations are presented in this abstract. The ultimate goal of this project is to incorporate this 6 DOF stage within a long range X-Y scanning system for nanometer pick-and-place capability over an area of 50 x 50 mm. The control strategy and early results from this system will be presented[1].

Introduction

This document discusses a 6 axis controller for a fine motion stage translator comprising a moving platform that is connected to a base via 6 piezoelectric actuators. The ultimate goal of this project is to incorporate this 6 DOF stage within a long range *X-Y* scanning system for nanometer pick-and-place capability over an area of 50 x 50 mm. The control strategy and early results from this system will be presented.

Experimental arrangement

During these initial tests, motion of the moving platform of the stage was monitored by a nest of six capacitance gages that monitored displacements against a cube mounted on top of the platform. It is noted that this cube added a further ≈360 gm to the moving stage at an offset of 75 mm from the center of the stage thereby altering its dynamic characteristics in terms of both damping and pole position, see results.

A mathematical model indicating key geometric parameters of the experimental set-up is shown in Fig. 1. In this figure, the moving platform is represented by the lower, larger, rectangular block. The three actuator pairs in coordinates *x*, *y* and *z* are identified by their orientation with the first subscript *A* indicating that it is an actuator and the second subscripts *A* and *B* identifying each actuator of the pair. As shown the latter subscript is chosen so that a counter-clockwise rotation would correspond to an extension of actuator *A* and a contraction of actuator *B*. Similar notation is used for the capacitance gages with the exception that the first subscript is a *P* to identify the parameter as representing a probe. The parameter *S* represents the separation between probe and actuator pairs with the subscripts discriminating between them.

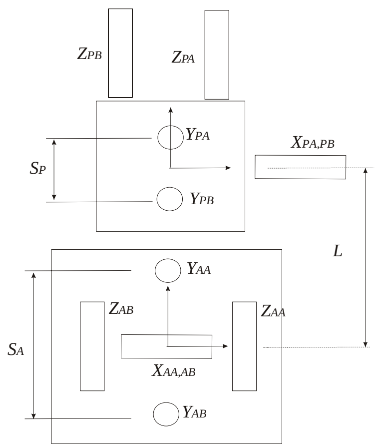

Figure 1: Model of the fine motion platform and capacitance-based position sensors

To determine poles and zeros in the 21 function of the frequency response matrix, initial dynamic tests using a dynamic signal analyzer were performed under open-loop control. These tests also indicate the cross coupling between coordinates. A 6 DOF controller has been developed and further tests were performed under closed-loop control.

System model and control

For the purpose of control, it is necessary to transform from the motion in the axes of the moving platform to an actuator drive demand as well as a transformation between the probe signals and the motion of the upper block. Based on the model of figure 1, the latter transformation to derive the motion of the center of the upper measurement block $\mathbf{q}$ (it is the control of this column matrix that is the goal of the control system) from the probe measurements $\mathbf{x}_\mathbf{P}$ is given by

$$\begin{Bmatrix} x \\ y \\ z \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} = \begin{bmatrix} 1/2 & 1/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & 1/2 \\ 0 & 0 & 1/S_P & -1/S_P & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/S_P & -1/S_P \\ 1/S_P & -1/S_P & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} X_{PA} \\ X_{PB} \\ Y_{PA} \\ Y_{PB} \\ Z_{PA} \\ Z_{PB} \end{Bmatrix} \tag{1}$$

or

$$\{\mathbf{q}\} = [\mathbf{B}]\{\mathbf{X_P}\}$$

The transformation between the actuator displacements $\mathbf{X_A}$ and an estimate of the motion of the upper block $\hat{\mathbf{q}}$ is given by

$$\begin{Bmatrix} X_{AA} \\ X_{AB} \\ Y_{AA} \\ Y_{AB} \\ Z_{AA} \\ Z_{AB} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & L & S_A/2 \\ 1 & 0 & 0 & 0 & L & -S_A/2 \\ 0 & 1 & 0 & L+S_A/2 & 0 & 0 \\ 0 & 1 & 0 & L-S_A/2 & 0 & 0 \\ 0 & 0 & 1 & 0 & S_A/2 & 0 \\ 0 & 0 & 1 & 0 & -S_A/2 & 0 \end{bmatrix} \begin{Bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ \hat{\theta}_x \\ \hat{\theta}_y \\ \hat{\theta}_z \end{Bmatrix} \tag{2}$$

or

$$\{\mathbf{X_A}\} = [\mathbf{A}]\{\hat{\mathbf{q}}\}$$

With the exception of one coupling term in θ_y and *x*, the orthogonality of the actuator pairs enables these transformations to be separated into three compact sets of transformations that are treated as nearly independent control loops for economy of computation.

The function of all components except for the plant are carried out by the computer and dSPACE system. Matrix computation and controller design is carried out in Mathworks Matlab™ while the resultant algorithms are processed in real time using dSPACE DS1103 controller hardware. At this present time, a simple integral controller is employed. The control error is computed as the difference between the measured displacements computed from the transformation of equation (1). The controller output is then transferred to the actuators after the transformation given by equation (2).

Results

For brevity, the results shown are restricted to those of linear translation only. A more complete discussion will be presented at the conference. Figure 2 shows the open loop frequency response of the platform in the three linear axes.

Coordinate	Gravest mode (Hz)	Pole height (dB)
x	208	26
y	301	12
z	524	26
θ_x	280	13
θ_y	208	20
θ_z	588	5

The gravest mode frequencies indicated by the poles in figure 2 was lowest in the x & y directions, see adjacent table. This was mainly due to the large offset between mass centroid of the capacitance electrode target block to the axis of the corresponding actuator pair while the z axis drive was coincident. Figure 3 shows the closed loop response to a force in z with the simultaneously measured responses in the other two axes. Amplitude of excitation in z was 100 nm so that -30 dB corresponds to an rms amplitude of 3 nm which is approaching the measurement resolution in these experiments.

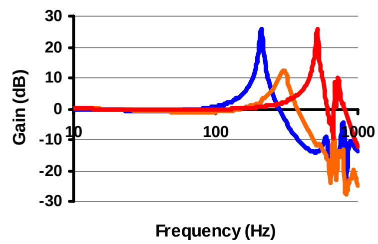

Figure 2: Open loop frequency responses of the three linear axes

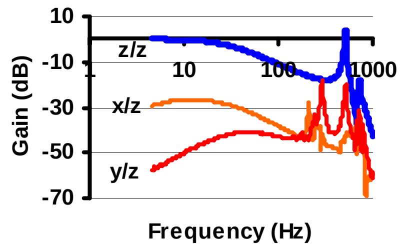

Figure 3: Closed loop response to demand in z axis with measured coupling in x & y

References

[1] This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.
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[3] Yang H., Seugling R.M., Jain P., Fagan T., Smith S.T., Hocken R.J., David Otten and David L. Trumper, 2004, A coarse/fine motion control stage; preliminary studies, *Proc. ASPE.*, **34**, 434 – 437.